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Statistical Properties of Brown Dwarf Companions: Implications for Different Formation Mechanisms

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ABSTRACT

The mass domain where massive extrasolar planets and brown dwarfs overlap is still poorly understood due to the paucity of brown dwarfs orbiting close to solar-type stars, the so-called brown dwarf desert. In this paper we collect all of available data about close brown dwarfs around solar type stars and their host stars from literature and study the demographics of the brown dwarf desert. The data clearly show a short period and a medium mass gap in the brown dwarf period-mass distribution diagram ($35 < m \sin i < 55 M_{\rm Jup}$ and $P < 100$ days), representing the "driest land" in the brown dwarf desert. Observation biases are highly unlikely to cause this gap due to its short period and medium mass, of which brown dwarfs can be easily detected by previous RV surveys. Brown dwarfs above and below this gap have significantly different eccentricity distribution, which not only confirms that this gap is real, but also implies that they may have different origins. Our further statistical study indicates that brown dwarfs below this gap may primarily form in the protoplanetary disk through disk gravitational instability, while brown dwarfs above this gap may dominantly form like a stellar binary through molecular cloud fragmentation. Our discoveries have offered important insights about brown dwarf formation mechanisms and their possible relationships with planet and star formation.

Key words: stars: brown dwarf – technique: radial velocity

1 INTRODUCTION

Brown dwarfs (BD) are in the mass range of approximately 13−80 Jupiter masses, having sufficient masses to burn deuterium but not enough to burn hydrogen in their inner cores (Burrows et al. 1997; Chabrier & Baraffe 2000; Burrows et al. 2001; Spiegel, Burrows, & Milsom 2011). The first discovery of a bona-fide BD (Rebolo et al. 1995; Nakajima et al. 1995; Oppenheimer et al. 1995; Basri et al. 1996; Rebolo et al. 1996) came in the same year as the discovery of the first extra-solar planet around a solar type star, 51 Peg b (Mayor & Queloz 1995). One of the major achievements of high-precision radial velocity (RV) surveys over the past two decades is the identification of a brown dwarf desert, a paucity of brown dwarf companions relative to planets within 3 AU around main-sequence FGKM stars (Marcy & Butler 2000; Grether & Lineweaver 2006). Although the induced reflex RV signal by a close BD companion on a solar type star is well within the detection sensitivities of the high precision RV surveys ($\sim 3 - 10$ m/s), only a few dozens are known (Reid & Metchev 2008; Sahlmann et al. 2011a and references therein) compared to over five hundred giant planets detected so far by RV technique. The California & Carnegie Planet Search measured an occurrence rate of 0.7% ± 0.2% from their sample of ~ 1000 target stars (Vogt et al. 2002; Patel et al. 2007), and the McDonald Observatory Planet Search shows a similar rate of 0.8% ± 0.6% from a search sample of 250 stars (Wittenmyer et al. 2009). Sahlmann et al. (2011a) obtained an upper limit of 0.6% for the frequency of close BD companions based on the uniform stellar sample of the CORALIE planet search, which contains 1600 solar type stars within 50 pc.

To assess the reality of the brown dwarf desert, Grether & Lineweaver (2006) performed a detailed investigation of the companions around nearby Sun-like stars. They found that approximately 16% of nearby Sun-like stars have close ($P < 5$ yr) companions more massive than Jupiter: $11\% \pm 3\%$ are stellar companions, $< 1\%$ are BDs, and $5\% \pm 2\%$ are giant planets. Although the close BDs are rare around solar type stars, Gizis et al. (2001) suggests that BDs might not be as rare at wide separations (see also Metchev & Hillenbrand 2004) as at close separations. Lafrenière et al. (2007) obtained a 95% confidence interval of $1.9^{+8.3}_{-1.5}\%$ for the frequency of $13{-}75 M_{\rm Jup}$ companions between 25−250AU in the Gemini Deep Planet Survey around 85 nearby young stars. Metchev & Hillenbrand (2009) inferred the frequency of BDs in 28−1590 AU orbits around young solar analogs is $3.2^{+3.1}_{-2.7}\%$ from an adaptive optics survey for substellar companions around 266 Sun-like stars.

BDs are traditionally believed to form like stars, through

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gravitational collapse and/or fragmentation of molecular clouds (Padoan & Nordlund 2004; Hennebelle & Chabrier 2008). A recently found self-gravitating clump of gas and dust has a mass ($0.015 - 0.03$ $M_{\odot}$) in the BD regime (André, Ward-Thompson, & Greaves 2012), which supports the idea that BDs could form like a star. On the other hand, companions with masses up to 10 $M_{\rm Jup}$ (Alibert et al. 2005) or even 38 $M_{\rm Jup}$ (Mordasini et al. 2009) may form in protoplanetary disks according to the standard core-accretion planet formation theory. Because of this, the brown dwarf desert is commonly interpreted as the gap between the largest mass objects that can be formed in protoplanetary disks, and the smallest mass clumps that can collapse and/or fragment in the vicinity of a protostar. The mass function of close stellar companions shows a linear decrease in log(M) toward the BD mass range from both stellar mass and planetary mass directions (Grether & Lineweaver 2006). In comparison, the mass function of isolated substellar objects seems to be roughly flat in log(M) down to masses $\sim$ 20 $M_{\rm Jup}$, both in the field and in clusters (Luhman et al. 2000; Chabrier 2002). This indicates that close BD companions may form in a different way from those formed in the field and clusters.

As such, statistical properties of close BD companions as well as how these properties are related to their host stars, contain a lot of information about the poorly understood BD formation mechanisms and their relationships with star and planet formations in close orbital environments. These statistics may also be important to investigating how additional important processes such as tidal evolution and disk-planet interaction affect close BD properties (e.g., Armitage & Bonnell 2002; Matzner & Levin 2005). Given that the close BD occurrence rate is $< 1\%$, currently there has yet been a single large, relatively uniform RV survey capable of producing a large homogeneous sample of BD companions for a meaningful statistical study (Marcy et al. 2000; Ge et al. 2008; Sahlmann et al. 2011a). However, all of the previous RV planet surveys have sufficient RV sensitivity and time baseline (at least more than 2 years, e.g., Ge et al. 2008; Ge et al. 2009; Eisenstein et al. 2011) to detect a majority of close BDs around solar type stars due to the large RV amplitude (on the order of $\sim$ 1000 m/s, vs. a few to a few tens m/s RV precisions in previous RV planet surveys). It is, therefore, possible to combine close BD companion samples together for a statistical study without major biases.

In this paper we assembled a catalog of all the BD companions discovered around solar type star from literature and used it to conduct a statistical study. We have found tentative evidence for the existence of two different populations of BD companions. We present the BD catalog assembled in this study in §2 , statistical properties of BD companions in §3 and discuss their implication for different BD formation scenarios in §4. We summarize our main results in §5.

2 CATALOG DESCRIPTION

We have collected data from literature about the currently known BD (candidates) companions around FGK type stars. Most of them have known Keplerian orbits, except for HIP 78530 (discovered by direct imaging; Lafrenière et al. 2011), KOI-205.01 (unpublished yet; Santerne et al. 2012) and KOI-554.01 (unpublished yet; Santerne et al. 2012). Properties of the BDs (minimum mass, period and eccentricity) and their host stars (mass, effective temperature, surface gravity and metallicity) are summarized in Table 1. For those which are transiting their parent stars or have astrometry measurements, true masses are also given besides $M \sin i$.

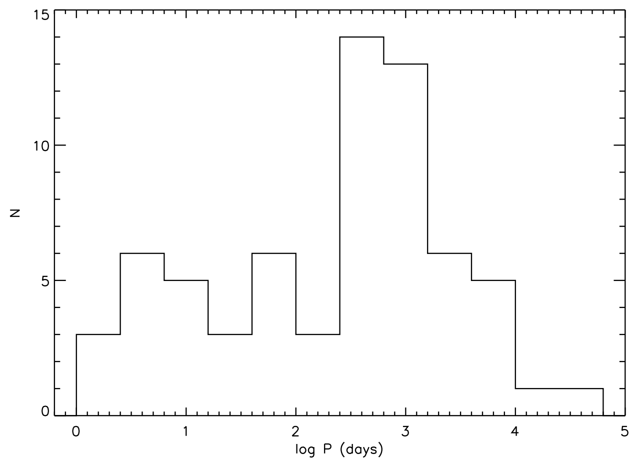

Figure 1. Period distribution of known BD companions around solar type stars.

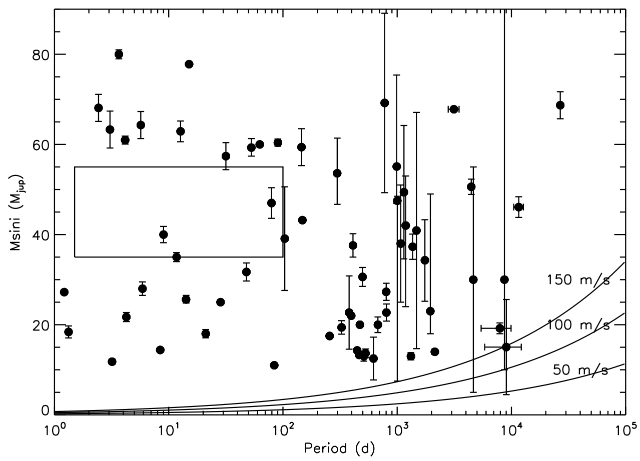

Figure 2. Cumulative mass distribution of brown dwarf candidates. Three lines with three RV precisions, 50 m/s, 100 m/s and 150 m/s, are also shown.

3 OBSERVED PROPERTIES OF BROWN DWARFS

3.1 Orbital Period Distribution

The distribution of orbital periods of BDs has two main features (Fig. 1): a relatively flat distribution inside $P \sim 100$ days and a sharp jump beyond $P \sim 100$ days. The drop beyond $P \sim 1000$ days is likely due to the observational incompleteness since 1) it is more difficult to detect a BD companion over a long period than a short period with RVs and 2) some RV surveys (such as the SDSS-III MARVELS, Ge et al. 2008; Ge et al. 2009; Eisenstein et al. 2011) do not cover beyond this period. It is evident that the number of BDs increases with the orbital period, even though RV and transit observations are biased toward discovering objects in short-periods. The position of the maximum of the distribution is unknown due to the different duration limit of most of the old surveys (several thousand days). This increasing distribution is consistent with the results from high contrast and high angular resolution imaging surveys, which find evidence

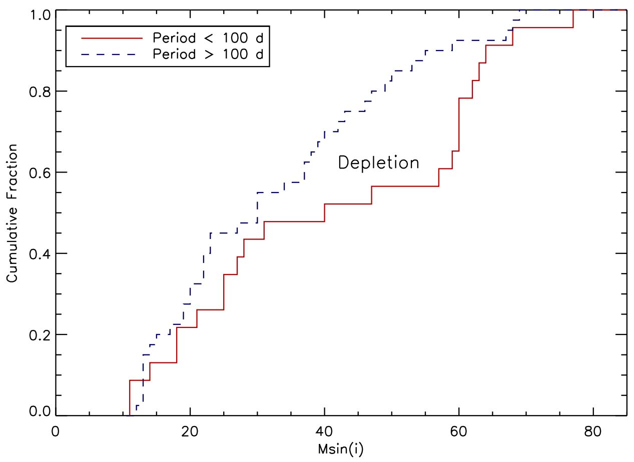

Figure 3. Cumulative mass distribution of brown dwarf companions. Brown dwarfs with periods greater and less than 100 days are shown as dashed and solid lines respectively.

for a higher fraction of BD companions at wide orbits than at close orbits (Lafrenière et al. 2007; Metchev & Hillenbrand 2009; Chauvin et al. 2010; Janson et al. 2012).

For comparison, both extrasolar giant planets (Cumming, Marcy, & Butler 1999; Udry, Mayor, & Santos 2003; Marcy et al. 2005; Udry & Santos 2007) and binaries (Duquennoy & Mayor 1991) show an increasing number distribution with period. However, there is no 3-day pile up with the BD distribution as shown in giant planets (Udry et al. 2003). The reason may be that BDs initially form in the protoplanetary disks further away from the host stars where protoplanetary disks have more materials to efficiently form BDs than at the close-in regions, and the migration mechanism may not efficiently move such a massive body to a short period orbit (Trilling et al. 1998; Nelson et al. 2000; Trilling, Lunine & Benz 2002). On the other hand, BDs forming at the same time as the primary stars may migrate inward quickly in the initial gas rich disks and thus be destroyed via mergers with the stars (Armitage & Bonnell 2002).

3.2 The Period-Mass Diagram

The period-mass distribution of BDs shows a statistically significant gap at the short period and medium mass region as illustrated in Fig. 2. In this plot, a rectangular area with $P < 100$ d and $35M_{Jup} < M < 55M_{\rm Jup}$ is highlighted to show the gap within which BDs are nearly depleted while there are numerous BDs around this region. It appears that this gap is real since it is unlikely caused by detection sensitivity (RV precision) or observation biases (due to survey incompleteness). Previous RV observations have detected many BDs with masses less than the lower limit ($\sim$35 M_{Jup}) of this region and also BDs with periods significantly longer than the period limit of this region ($\sim$100 days). RV sensitivities with three moderate RV precisions, 50 m/s, 100 m/s and 150 m/s, shown in Fig. 2 clearly illustrate that any of BDs in the gap should be detected easily with these moderate RV precisions. To further verify if this feature is real, we divided the BD sample into two groups according to their periods ($P < 100$ days and $P > 100$ days) and plotted their mass cumulative histograms in Fig. 3 for comparison. It is apparent that a depletion of BDs with masses between 35 and $55M_{\rm Jup}$ appears in the cumulative histogram for the short period group while no depletion of BDs appears in the cumulative histogram for the long period group. We carried out a simple Monte Carlo experiment to test the emptiness of this gap on the period-mass diagram. There are a total of 25 BDs with period shorter than 100 days in our BD sample. We assumed simply that their masses are uniformly distributed between 13 and $80M_{Jup}$. Then we drew their masses randomly from this uniform distribution and counted how many of them will fall in the mass range of 35 to $55M_{\rm Jup}$. We found the probability that less than 3 BDs will fall in this gap is 0.9%, which corresponds to a 2.6σ significance. A larger BD sample in the future will be better to assess the significance of this gap.

The appearance of this depleted region in the BD period-mass diagram has naturally divided BDs into two mass groups: one with masses greater than $42.5M_{\rm Jup}$ and the other less than $42.5M_{\rm Jup}$. Their properties and origins may be different. We further explore properties of these two groups and study possible origins.

3.3 Orbital Eccentricity Distribution

The orbital eccentricities show great difference for the two BD groups with masses greater and lower than $42.5M_{\rm Jup}$, respectively. Fig. 4 shows the period-eccentricity distribution of all known BDs. The period-eccentricity distribution of BDs with masses greater than $42.5M_{Jup}$ is consistent with a circularization limit of $\sim$ 12 days, which is similar to that found in nearby stellar binaries (Raghavan et al. 2010). It is clear that there are a significant number of BDs with 300 d $< P <$ 3000 d and $e < 0.4$ for BDs with masses lower than $42.5M_{\rm Jup}$, but no BDs with masses greater than $42.5M_{\rm Jup}$. We have done a two-dimensional Kolmogorov-Smirnov (K-S) test for the period-eccentricity distribution of BDs with masses greater and lower than $42.5M_{\rm Jup}$. The probability that these two BD samples are drawn from the same distribution in the period-eccentricity plane is 1.7%.

Next we are going to compare the period-eccentricity distribution of the BDs to that of stellar binaries. Halbwachs et al. (2003) have studied the statistical properties of a sample of 89 FGK type main-sequence binaries with periods up to 10 year. Here we choose to use their 89 binary sample for our comparison. To compare the period-eccentricity distribution between BDs and stellar binaries we made use of a two-dimensional K-S test. The probability for the period-eccentricity distribution to be the same is 18% between BDs with masses above $42.5M_{\rm Jup}$ and the stellar binary sample, and 0.1% between BDs with masses below $42.5M_{\rm Jup}$ and the stellar binary sample. These results suggest that BDs with masses greater than $42.5M_{\rm Jup}$ have a very similar period-eccentricity distribution to that of stellar binaries, and their formation mechanisms may be similar.

The difference of the orbital eccentricities for BDs with different masses is further illustrated in the mass-eccentricity plot shown in Fig. 5. By including all currently known planets (from exoplanet.org) and brown dwarfs (this paper) in this plot, a clear trend is shown: all the known giant planets and BDs with masses below $\sim$ $42.5M_{\rm Jup}$ have the eccentricity distribution following a trend, i.e., the more massive the giant planet/BD is, the lower maximum eccentricity it tends to have while BDs above this mass threshold do not show such a trend, instead showing more diversity in their eccentricities.

3.4 Metallicity of the BD Host Stars

The BD host stars in this study have a mean metallicity of [Fe/H] $= -0.04$ with a standard deviation of 0.28. For comparison,

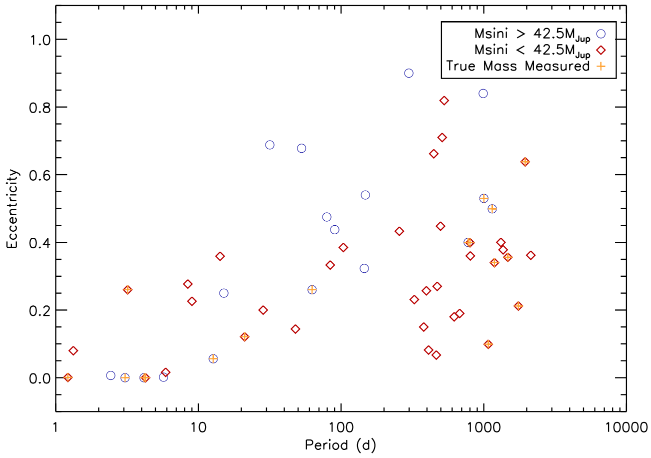

Figure 4. Period-eccentricity distribution of brown dwarf candidates. Brown dwarf candidates with masses above and below $42.5M_{\rm Jup}$ are shown as circles and diamonds. Brown dwarf candidates with true masses measured using transiting observations or astrometry measurements are shown as crosses.

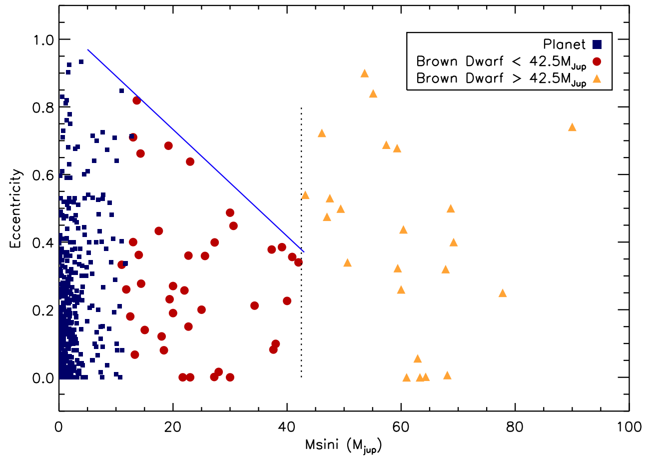

Figure 5. Mass-eccentricity distribution of exoplanets and brown dwarf candidates. The solid line shows a trend that the more massive the giant planet/BD is, the smaller maximum eccentricity it tends to have, which breaks at $\sim 42.5M_{\rm Jup}$. The vertical dotted line shows $M\sin i = 42.5M_{\rm Jup}$. Planets are shown as squares. Brown dwarfs with masses above and below $42.5M_{\rm Jup}$ are shown as triangles and circles respectively.

Raghavan et al. (2010) has carefully studied a sample of 454 nearby solar type stars, which have a mean metallicity of -0.14 with a standard deviation of 0.25. Six stars in that sample have BD companions, which have a mean metallicity of [Fe/H]= -0.05. The mean metallicity of our BD sample is slightly higher than the mean metallically of volume limited nearby FGK dwarf stars. For example, Favata, Micela, & Sciortino (1997) have analyzed a volume limited sample of 91 G and K dwarfs, yielding a mean metallicity of [Fe/H]= -0.08 with a standard deviation of 0.26. Nordström et al. (2004) have derived metallicity for 16682 nearby F and G dwarf stars with a mean of -0.14 and a dispersion of 0.19 dex. Sousa et al. (2011) found that a mean metallicity for the CORALIE survey sample of 1248 stars and the HARPS survey sample of 582 stars is [Fe/H]=-0.11 and -0.10, respectively. However, since some exoplanet surveys choose samples biased towards metal rich stars (e.g., Valenti & Fischer 2005), the slightly higher mean metallicity of BD host stars is possibly caused by the sample bias.

After comparing the BD host star metallicities with the volume limited sample from Sousa et al. (2011) and the planet search sample from Valenti & Fischer (2005), we find that the BD host star metallicity distribution is consistent with the combination of these two samples. This means we cannot interpret the BD host star sample as metal rich. We compared metallicities of BD host stars with that of giant planet ($1M_{\rm Jup} < m\sin i < 5M_{Jup}$) host stars. The data of giant planet host stars is taken from the Exoplanet Orbit Database (Wright et al. 2011). A K-S test shows that the probability of these two samples selected from the same distribution is 2×10^{-4}. This indicates that the two samples are significantly different from each other.

We investigated the correlation between BD host star metallicities and BD masses. The Spearman's rank correlation coefficient of the BD mass and their host star metallicity is 0.07 with a 61% significance, suggesting there is no significant correlation between the BD mass and their host star metallicity.

We also divided the BD companions into two subsample according to their masses. The cumulative metallicity distribution for host stars with BD companion masses above and below $42.5M_{\rm Jup}$ is shown in Fig. 6. The main difference between these two distribution is at the lower metallicity end. Currently no BDs with masses greater than $42.5M_{\rm Jup}$ have been found around stars with [Fe/H]<-0.5, while several BDs with masses lower than $42.5M_{\rm Jup}$ have been found in this metallicity regime. A K-S test has been conducted to show that the probability of these two sample metallicities are drawn from the same distribution is 70%, which suggests there is no significant difference between these two samples regarding their metallicity distribution.

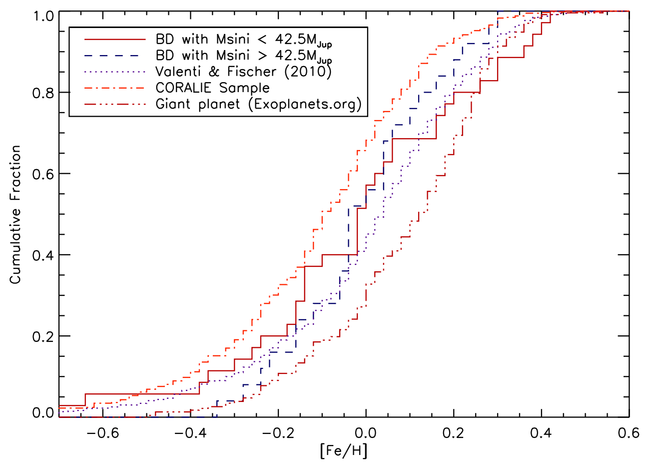

Figure 6. Cumulative metallicity distribution of host stars with BD companion masses above (dashed line) and below (solid line) $42.5M_{\rm Jup}$. Also shown for comparison are cumulative metallicity distribution of the planet search sample from Valenti & Fischer (2005), the CORALIE planet search sample (Sousa et al. 2011) and giant planet sample from the Exoplanet Orbit Database (Wright et al. 2011).

4 DISCUSSION

4.1 Two Different Brown Dwarf Populations

Our study suggests that BDs with masses lower than $\sim 43M_{\rm Jup}$ have an eccentricity distribution consistent with that of giant plan-

ets in the mass-eccentricity diagram while BDs with masses above $\sim 43M_{\rm Jup}$ have the star-like eccentricity distribution (Figure 5). Our mass limit is consistent with the minimum of the mass functions of planet and stellar companions in the BD mass region, $43^{+14}_{-23}M_{\rm Jup}$, derived by Grether & Lineweaver (2006) using their stellar companion and giant planet sample within 50 pc around the sun. This mass function minimum is also consistent with that derived by Sahlmann et al. (2011b), who found a void in the mass range between 25 and 45 $M_{\rm Jup}$ using the data from the CORALIE radial-velocity survey. They further suggested that there may be a possible dividing line between massive planets and substellar companions. Schneider et al. (2011) has chosen arbitrarily and probably provisionally $25M_{\rm Jup}$ as the upper limit of massive planets based on previous studies (e.g., Sahlmann et al. 2011b; Baraffe, Chabrier, & Barman 2010).

Our BD sample is, therefore, naturally divided into two different groups with the mass limit of $\sim 42.5M_{\rm Jup}$. The eccentricity distribution of low mass BDs appears to be consistent with the prediction from the "planet-planet scattering" model (Rasio & Ford 1996; Ford & Rasio 2008; Chatterjee et al. 2008), while the eccentricity distribution of massive BDs appears to be similar to that of stellar binaries (Halbwachs et al. 2003) as shown in § 3.3. The eccentricity distributions of these two groups support that BDs may form differently: BDs below this mass limit form in protoplanetary disks around host stars, and above this mass limit form like stellar binary systems. This is supported by our analysis results. The existence of a large population of long period low eccentricity BDs ($P > 300$ days and $e < 0.4$) serves as evidence to support the BD formation scenario in the protoplanetary disks for those companions with masses below 42.5$M_{\rm Jup}$. While the lack of long period and low eccentric BD companions with masses above 42.5$M_{\rm Jup}$ appears to support the BD formation scenario like stellar binary formation. Nevertheless, a small number of BDs in each of these two mass regions may form in an opposite formation mechanism, but our sample is not sufficient to distinguish these minor groups.

4.2 BD formation mechanisms

Our study of metallicity distribution of BDs appears to support the disk instability mechanism (Boss 1997) for those BDs formed in the planetary disks, while it is inconsistent with the prediction of core-accretion formation mechanism (Pollack et al. 1996; Ida & Lin 2004; Alibert et al. 2005). Currently, there are two hotly contested theories about giant planet formations: core-accretion and disk gravitational instability. In the core-accretion scenario, giant planets form more efficiently around metal rich planetary disks than metal poor planetary disks because the higher the grain content of the disk is, the easier the metal core is to build for giant planets (Pollack et al. 1996; Ida & Lin 2004; Alibert et al. 2005). In contrast, the disk gravitational instability process allows similar formation efficiency for both metal rich and metal poor giant planets. Previous results show strong correlation between metallicity and giant planet occurrence rate around solar type stars (Santos, Israelian, & Mayor 2001; Valenti & Fischer 2005; Johnson et al. 2010) strongly support the core-accretion formation scenario for giant planet formation (Pollack et al. 1996; Ida & Lin 2004; Alibert et al. 2005). However, our result, showing no correlation between the BD occurrence rate and metallicity, appears to support the disk instability mechanism for formation of BDs in planetary disks.

For stellar companions, there appears to be a weak anti-correlation between metallicity and stellar companion occurrence rate (Raghavan et al. 2010), i.e., lower-metallicity clouds might be more likely to fragment to form binary stars. If this applies to massive BDs, then we expect this anti-correlation. However, our current sample is too small to tell, but is at least not inconsistent with this statistics.

4.3 Upper Mass limit of Planets

Our study appears to help to address the upper mass limit of "planets". Here we define a "planet" as an object formed in a protoplanetary disk from the companion formation point of view. It has been long known that the low mass end of brown dwarfs overlaps the high mass end of massive planets formed in protoplanetary disks. From theoretical simulations, planets with masses up to 10 $M_{\rm Jup}$ (Alibert et al. 2005) or even 38 $M_{\rm Jup}$ (Mordasini et al. 2009) may form in protoplanetary disks. However, it is difficult to determine the upper mass limit of planet from observations since the high mass planets detected may actually be brown dwarfs formed as low-mass binaries. One way to tackle this problem is to search for debris disk around massive planet/BD host star, which support the idea that these objects are formed like a planet. Moro-Martín et al. (2010) have found evidence of debris disk around two massive planet host star (HD 38529 and HD 202206), which supports formation of planets up to 17 $M_{\rm Jup}$ in a protoplanetary disk. The other way to resolve this problem is through the study of mass spectrum of massive planets/BD. Motivated by the observed mass distribution, this planet upper mass limit has been set at around $43^{+14}_{-23}M_{\rm Jup}$ (Grether & Lineweaver 2006) or 25 $M_{\rm Jup}$ (Sahlmann et al. 2011b; Schneider et al. 2011). Analysis conducted in this paper was also able to provide a clue about this upper mass limit. The cumulative BD mass distribution (Fig. 3) suggests this limit is in the range $30 - 60$ $M_{\rm Jup}$ and mass-eccentricity relation (Fig. 5) suggests that this limit is around 43 $M_{\rm Jup}$. It appears that the upper limit is around 43 $M_{\rm Jup}$, which is consistent with the result found by Grether & Lineweaver (2006), but is slightly larger than that from (Sahlmann et al. 2011b).

5 SUMMARY

We have searched literature and presented a catalog of BD companions around solar type stars found by radial velocity, transiting and astrometry observations. We have studied distribution of different parameters of BD companions around solar type star, and found that:

(1) BD companions have an increasing distribution with period, similar to giant planets and low-mass binaries;
(2) BD companions are almost depleted at $P < 100$ d and $30M_{Jup} < M < 55M_{\rm Jup}$ in the period-mass diagram;
(3) BD companions with masses below $42.5M_{\rm Jup}$ have eccentricity distribution consistent with that of massive planets;
(4) BD companions with masses above $42.5M_{\rm Jup}$ have eccentricity distribution consistent with that of binaries, which shows the expected circularization for periods below 12 days, caused by tidal forces over the age of the Galaxy, followed by a roughly flat distribution;
(5) Host stars of BD companions are not metal rich, and have significantly different metallicity distribution when comparing with host stars of giant planets, suggesting a formation scenario at least partly different from the core-accretion scenario.

The distribution of BD and their host star properties presented

in this paper may lend support to such a picture: (1) BD companions with masses below $42.5M_{\rm Jup}$ form in a protoplanetary disk through the the instability-fragmentation scenario, and their eccentricity is excited through scattering with other objects formed in this disk or interactions with disk/third body; (2) BD companions with masses above $42.5M_{\rm Jup}$ form like stars, through molecular cloud fragmentation, similar to the formation of a stellar binary system.

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Table 1. Close brown dwarfs (candidate) companions to solar-type stars

Object	M_c (M_{Jup})	$M_c \sin i$ (M_{Jup})	Period (day)	Eccentricity	$M_\star$ ($M_\odot$)	$T_{\rm eff}$ (K)	$\log(g)$ (cgs)	[Fe/H]	References
HD 30501	$\cdots$	90 ± 12	$2073.6^{+3.0}_{-2.9}$	0.741	0.81 ± 0.02	5223±50	4.56±0.10	-0.06 ± 0.06	1
HD 43848	101.8 ± 15.0	24.5 ± 1.6	2354.3±8.9	0.703	0.89 ± 0.02	5334±92	4.56±0.15	0.22 ± 0.06	1, 56
HD 52756	$\cdots$	$59.3^{+2.0}_{-1.9}$	52.8657±0.0001	0.6780±0.0003	0.83 ± 0.01	5216±65	4.47±0.11	0.13 ± 0.05	1
HD 89707	$\cdots$	$53.6^{+7.8}_{-6.9}$	298.5±0.1	$0.900^{+0.039}_{-0.035}$	0.96 ± 0.04	6047±50	4.52±0.10	-0.33 ± 0.06	1
HD 167665	$\cdots$	50.6 ± 1.7	$4451.8^{+27.6}_{-27.3}$	0.340 ± 0.005	1.14 ± 0.03	6224±50	4.44±0.10	-0.05 ± 0.06	1
HD 189310	$\cdots$	$25.6^{+0.9}_{-0.8}$	14.18643±0.00002	0.359±0.001	0.83 ± 0.02	5188±50	4.49±0.10	-0.01 ± 0.06	1
HD 4747	$\cdots$	46.1 ± 2.3	$11593.2^{+1118.6}_{-1117.6}$	0.723±0.013	0.81 ± 0.02	5316±50	4.48±0.10	-0.21 ± 0.05	1
HD 211847	$\cdots$	19.2 ± 1.2	$7929.40^{+1999.1}_{-2500.2}$	$0.685^{+0.068}_{-0.067}$	0.94 ± 0.04	5715±50	4.49±0.10	-0.08 ± 0.06	1
HD 180314	$\cdots$	22.0	396.03±0.62	0.257±0.010	2.6 ± 0.3	4917±100	2.98±0.12	0.2 ± 0.09	3
HD 13189	$\cdots$	20.0	471.6±6.0	0.27±0.06	7	5000±100	2.0±0.1	0.0 ± 0.10	4
HD 30339	$\cdots$	77.8	15.0778±0.000	0.25	1.1	6074±100	4.37±0.10	0.21 ± 0.10	4
HD 65430	$\cdots$	67.8	3138±342	0.32	0.78	5183±100	4.55±0.10	-0.04 ± 0.10	4
HD 140913	$\cdots$	43.2	147.968±0.000	0.54	0.98	6048±100	4.57±0.10	0.07 ± 0.10	4
HD 174457	$107.8^{+23.8}_{-24.1}$	$\cdots$	840.8±0.05	0.23 ± 0.01	1.19	5852±100	4.08±0.10	-0.15 ± 0.10	4
HD 38529c	$17.6^{+1.5}_{-1.2}$	13.99 ± 0.59	2136.14±0.29	0.362±0.002	1.48 ± 0.05	5697	3.94±0.10	$+0.27 \pm 0.05$	5
HD 91669	$\cdots$	30.6 ± 2.1	497.5±0.6	0.448 ± 0.002	$0.914^{+0.018}_{-0.087}$	5185±87	4.48±0.20	$+0.31 \pm 0.08$	6
11Com	$\cdots$	19.4 ± 1.5	326.03±0.32	0.231 ± 0.005	2.7 ± 0.3	4742±100	2.31±0.10	-0.35 ± 0.09	7
HD 119445	$\cdots$	37.6 ± 2.6	410.2±0.6	0.082±0.007	3.9 ± 0.4	5083±103	2.40±0.17	0.04 ± 0.18	8
HD 131664	$23^{+26.0}_{-5.0}$	$\cdots$	1951±41	0.638±0.02	1.10 ± 0.03	5886±21	4.44±0.10	$+0.32 \pm 0.02$	9, 56
GJ 595	$\cdots$	60.0 ± 0.0	62.6277±0.0001	0.26±0.001	0.28	3500±100	4.83±0.10	0.0 ± 0.10	4
HD 162020	$\cdots$	14.4 ± 0.04	8.428198±0.000056	0.277 ± 0.002	0.75	4830±80	4.76±0.25	$+0.01 \pm 0.11$	12
HD 168443	34.3 ± 9.0	$\cdots$	1748.2±1.0	0.2122±0.0020	1.01 ± 0.05	5555±40	4.10±0.12	$+0.10 \pm 0.03$	1, 12, 22
HD 180777	$\cdots$	25.0 ± 0.0	28.44±0.01	0.20	1.7 ± 0.1	7250	4.34	-0.16	1, 24, 25
HD 190228	49.4 ± 14.8	$\cdots$	1146±16	0.50±0.04	0.83	5360±40	4.02±0.10	-0.24 ± 0.06	1, 26
HD 191760	$\cdots$	38.17 ± 1.02	505.65±0.42	0.63 ± 0.01	$1.28^{+0.02}_{-0.10}$	5821±82	$4.13^{+0.05}_{-0.04}$	0.29 ± 0.07	1, 27
HD 202206	$\cdots$	17.5	256.20 ±0.03	0.433 ± 0.001	1.15	5765±40	4.75±0.20	0.37 ± 0.07	1, 12, 28
HIP 21832	40.9 ± 26.2	$\cdots$	1474.9±10.2	0.356 ± 0.095	1.0 ± 0.0	5554±70	4.32±0.10	-0.63 ± 0.10	17
HD 14651	$\cdots$	47.0 ± 3.4	79.4179±0.0021	0.4751±0.0010	0.96 ± 0.03	5491±26	4.45±0.03	-0.04 ± 0.06	18
HD 30246	$\cdots$	$55.1^{+20.3}_{-8.2}$	990.7±5.6	0.838 ± 0.081	1.05 ± 0.04	5833±44	4.39±0.04	$+0.17 \pm 0.10$	18
HD 92320	$\cdots$	59.4 ± 4.1	145.4±0.01	0.323	0.92 ± 0.04	5664±24	4.48±0.03	-0.10 ± 0.06	18
HD 22781	$\cdots$	13.65 ± 0.97	528.07±0.14	0.8191±0.0023	0.75 ± 0.03	5027±50	4.60±0.02	-0.37 ± 0.12	18
HD 137510	20.0-60.0	27.3 ± 1.9	801.30±0.45	0.3985±0.0073	1.36 ± 0.04	6131±50	4.02±0.04	0.38 ± 0.13	10, 11, 18,
HIP 5158	$\cdots$	15.04 ± 10.55	9017.76±3180.74	0.14±0.10	0.780 ± 0.021	4962±89	4.37±0.20	0.10 ± 0.07	29, 52
HD 41004B	$\cdots$	18.37 ± 0.22	1.328300±0.000012	0.081±0.012	0.40 ± 0.04	$\cdots$	$\cdots$	$\cdots$	30
HAT-P-13c	$\cdots$	14.28 ± 0.28	446.27±0.22	0.6616±0.0054	$1.22^{+0.05}_{-0.10}$	5640±90	4.13±0.04	0.430 ± 0.08	31
BD+202457b	$\cdots$	22.7 ± 8.1	379.63±2.01	0.15 ± 0.03	2.8 ± 1.5	4137±10	1.51±0.05	-1.00 ± 0.07	32
BD+202457c	$\cdots$	13.2 ± 4.7	621.99±10.20	0.18 ± 0.06	2.8 ± 1.5	4137 ±10	1.51±0.05	-1.00 ± 0.07	32
HD 137759	$\cdots$	12.7 ± 1.08	511.098±0.089	0.7124±0.0039	1.80 ± 0.23	4500 ±110	2.74±0.10	0.03 ± 0.10	11, 33, 35
NGC 2423-3b	$\cdots$	10.64 ± 0.93	714.3±5.3	0.21±0.07	2.4 ± 0.2	$\cdots$	$\cdots$	$\cdots$	36, 37
NGC 4349−127b	$\cdots$	20.0 ± 1.73	678.0±6.2	0.19	3.9 ± 0.3	4569 ±69	2.08±0.35	-0.13 ± 0.18	36, 37
HD 16760b	$\cdots$	13.13 ± 0.56	466.47±0.35	0.084±0.003	0.78 ± 0.05	5629±44	4.47±0.06	$+0.067 \pm 0.05$	38
HD 10697	38 ± 13	$\cdots$	1075.0±1.5	0.099±0.007	$1.112^{+0.026}_{-0.02}$	5680 ±44	4.12±0.06	0.19 ± 0.03	40, 41, 42
HD 114762	$\cdots$	10.99 ± 0.09	83.9152±0.0028	0.3325	0.89 ± 0.09	5950 ±44	4.54±0.06	-0.65 ± 0.03	11, 34, 43
TYC 2534-698-1	$\cdots$	39.1 ± 11.5	103.698±0.111000	0.385	0.998 ± 0.040	5700 ±80	4.50±0.10	-0.25 ± 0.06	44
TYC 2949-557-1	$\cdots$	64.3 ± 3.0	5.69449±0.00029	$0.0017^{+0.0019}_{-0.0017}$	1.25 ± 0.09	6135 ±40	4.4±0.1	0.32 ± 0.01	45
TYC 1240-945-1	$\cdots$	28.0 ± 1.5	5.8953±0.0004	0.015±0.011	1.37 ± 0.11	6186 ±92	3.89±0.07	-0.15 ± 0.04	16
HIP 67526	$\cdots$	62.6 ± 0.6	90.2695±0.0188	0.4375±0.0040	1.11 ± 0.08	6004 ±29	4.55±0.15	0.04 ± 0.05	63
TYC 2930-872-1	$\cdots$	68.1 ± 3.0	2.430420±0.000006	0.0066±0.0010	1.21 ± 0.08	6427 ±33	4.52±0.14	-0.04 ± 0.05	58
TYC 2087-255-1	$\cdots$	40.0 ± 1.8	9.0090±0.0004	0.226±0.011	1.16 ± 0.08	5903 ±42	4.07±0.16	-0.23 ± 0.07	21
TYC 3130-160	$\cdots$	57.4 ± 3.0	31.66±0.023	0.688	1.0 ± 0.1	5104±50	4.43±0.10	0.01 ± 0.05	62
HIP 78530	$\cdots$	23 ± 3	$\sim 4.38 \times 10^6$	0 (fixed)	2.5 ± 0.2	10500±500	$\cdots$	$\cdots$	46
HD 5388b	69.2 ± 19.9	$\cdots$	777.0±4.0	0.40±0.02	1.21 ± 0.10	6297±32	4.28±0.06	-0.27 ± 0.02	48, 53

Table 1 (cont'd)

Object	M_c (M_{Jup})	$M_c \sin i$ (M_{Jup})	Period (day)	Eccentricity	$M_\star$ ($M_\odot$)	$T_{\rm eff}$ (K)	$\log(g)$ (cgs)	[Fe/H]	References
HR 7672b	68.7 ± 3.0	$\cdots$	$26772^{+803.5}_{-1059.2}$	0.5	1.08 ± 0.04	5883$\pm$59	4.42$\pm$0.06	0.05 ± 0.07	49
HD 175679	$\cdots$	37.3 ± 2.8	1366.8$\pm$5.7	0.378$\pm$0.008	2.7 ± 0.3	4844$\pm$100	2.59$\pm$0.10	-0.14 ± 0.10	50
HD 136118	42^{+11}_{-18}	12.0$\pm$0.47	1188.0$\pm$2.0	0.34$\pm$0.01	1.24$\pm$0.07	6097$\pm$44	4.16$\pm$0.09	-0.01$\pm$0.05	59, 60
HD 217786	$\cdots$	13.0$\pm$0.8	1319 $\pm$4	0.40$\pm$0.05	1.02$\pm$0.03	5966$\pm$65	4.35$\pm$0.11	-0.135$\pm$0.043	61
WASP-30	60.96 ± 0.89	$\cdots$	4.156736$\pm$0.000013	0 (adopted)	1.17 ± 0.03	6201$\pm$97	4.28$\pm$0.01	-0.03 ± 0.10	13
COROT-15	63.3 ± 4.1	$\cdots$	3.06036$\pm$0.00003	0 (adopted)	1.32 ± 0.12	6350$\pm$200	4.3$\pm$0.2	0.10 ± 0.20	14
LHS 6343	62.9 ± 2.3	$\cdots$	12.71382$\pm$0.00004	0.056$\pm$0.032	0.370 ± 0.009	$\cdots$	4.851$\pm$0.008	0.04 ± 0.08	15
Corot-3b	21.66 ± 1.00	$\cdots$	4.25680$\pm$0.000005	0 (adopted)	1.37 ± 0.09	6740$\pm$140	4.22$\pm$0.07	-0.02 ± 0.06	19
XO-3b	11.8 ± 0.59	$\cdots$	3.1915239$\pm$0.0000068	0.26$\pm$0.017	1.213 ± 0.066	6429$\pm$100	4.244$\pm$0.041	-0.177 ± 0.080	20
KOI-423b	$18.0^{+0.93}_{-0.91}$	$\cdots$	21.0874$\pm$0.0002	$0.121^{+0.022}_{-0.023}$	$1.1^{+0.07}_{-0.06}$	6260$\pm$140	4.1$\pm$0.2	-0.29 ± 0.10	23
KELT-1b	$27.23^{+0.5}_{-0.48}$	$\cdots$	1.217514$\pm$0.000015	$0.0099^{+0.01}_{-0.0069}$	1.324 ± 0.026	6518$\pm$50	$4.229^{+0.012}_{-0.019}$	0.008 ± 0.073	56
KOI-205.01	35	$\cdots$	11.72	$\cdots$	$\cdots$	5060	4.57	-0.17	57
KOI-554.01	80	$\cdots$	3.66	$\cdots$	$\cdots$	5835	4.64	-0.08	57

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